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SURFACE AND ALLIED STUDIES IN SILICON SOLAR CELLS

THIRD QUARTERLY REPORT
Dec. 24, 1983 - Mar. 23, 1984

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ABSTRACT

We report significant improvements in the short-circuit current-decay method of measuring the recombination lifetime τ and the back surface recombination velocity S of the quasineutral base of silicon solar cells. The improvements include a new circuit implementation that increases the speed of switching from the forward-voltage to the short-circuit conditions. They also include a supplementation of this method by some newly developed techniques employing small-signal admittance as a function of frequency ω, which involve significant contributions by Professor Neugroschel. This supplementation is highly effective for determining τ for cases in which the diffusion length L greatly exceeds the base thickness W. Representative results on different solar cells are reported.

We outline briefly some advances made in the understanding of passivation provided by the polysilicon/silicon heterojunction. Recent measurements by Professor Neugroschel demonstrate that $S \ll 10^4$ cm/s derive from this method of passivation.

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I. INTRODUCTION

This report describes technical findings of the third
quarter of contract no. 956525: December 27, 1983 to March 23,
1983. For a general statement of the objectives of the contract
the reader may consult the first and second quarterly reports.

In Sec. II, we report significant improvements in the short-
circuit current-decay method of measuring the recombination
lifetime τ and the back surface recombination velocity S of the
quasi-neutral base of silicon solar cells. The earlier version of
this method appeared in Quarterly 1 and recently in a journal
paper (Jung, Lindholm, and Neugroschel, 1984). The improvements
consist of a new circuit implementation that increases the speed
of switching and of a new selection of observables (discussed in
Quarterly 2, Sec 3.2.1, "Sensitivity studies...."). Both of
these improvements decrease the error bars in the determination
of τ and S. The efficacy of the improved method is demonstrated
by the measurement of over tendifferent solar cells, including
both p-base and n-base devices.

We believe that the method reported here is the most
reliable and accurate method available for the determination of τ
and S. Because it is a transient electrical method, it enables a

fast determination of these parameters. Moreover, the measurement configuration is inexpensive.

In Sec III, we outline some advances made in the understanding of the physical mechanisms underlying the passivation provided by polysilicon/silicon heterojunctions at surfaces. A review of the efficacy of such heterojunctions in increasing the common-emitter current gain β of silicon bipolar transistors, given here, demonstrates the efficacy of this heterojunction as a surface passivant. Recent measurements by the author's colleague, NEUGROSCHEL (1984), show a small effective surface recombination velocity S on a heavily doped emitter of a bipolar transistor: $S << \sim 10^4$ cm/s. This compares with $S \sim 10^6$ cm/s for minority holes at an unpassivated surface.

The review in Sec III is related to paragraph (a), items (5) and (6), of the statement of work for contract no. 956525, and prepares the way for our investigations on Si solar cells planned for the future. The brief review of Sec. II provides only a sketch of the studies on the polysilicon/silicon heterojunction. A fuller discussion elaborating on this brief review is planned for the final report for this contract.

The findings reported in Sec II may be regarded as new technology. The method described there is new and, we think,

superior to other methods available, and its development was
supported fully by this contract.   Note, however, that we make no
claims that the experimental set-up is optimized.   Rather, we
regard it as adequate for the purposes to which it is put.

The review given in Sec. III seeks only to sketch the
reasons for considering the polysilicon/silicon heterojunction as
a useful passivant for the surfaces of silicon solar cells.   No
claims are made in this report for advances by the author in the
understanding of the heterojunction.   For more detailed ideas
about the exciting potential of this heterojunction in silicon
solar cell design, JPL personnel are invited to review the recent
proposal submitted by the author.

In Sec. IV, we outline the projected or realized benefits
implicit in this report and make recommendations accordingly.

II. IMPROVEMENT OF SHORT-CIRCUIT-CURRENT DECAY METHOD FOR DETERMINING τ AND S OF THE QUASI-NEUTRAL BASE

Recently we have proposed and illustrated a new method for measuring the surface recomb. ation velocity S and the recombination lifetime τ in the quasineutral base of silicon solar cells and solar cells of other semiconductors (Jung, Lindholm and Neugroschel, 1984). Apart from the literature reference just made, Quarterly Reports 1 and 2 discussed this method.

In the short-circuit decay approach, for t < 0, a forward voltage has distributed excess holes and electrons throught the volume of the solar cell. Then a switch establishes a short circuit across the solar cell at t ≈ 0. For t > 0, the resulting transient decay is a key observable. The decay results from the recombination of the excess carriers within the volume of the device and at its surfaces.

The short-circuit decay method has an advantage compared with other methods. This follows from the dielectric relaxation and the drifting of excess holes that yields a junction space-charge region (junction transition region) in which practically no excess holes and electrons exist after about 10 ps. have passed after the switch closes. Thus this carrier storage does not distort the transient decay. Such distortion obscures the interpretation of other transient methods for determining S and τ

(Jung, Lindholm, and Neugroschel, 1984).

For germanium, for which most of the commonly used transient methods was developed, the error thus introduced is negligible; the excess carrier storage in the junction transition region for forward voltage is much less than the storage in the quasineutral base region. This is not so for Si or GaAs. The larger energy gaps and smaller intrinsic denisities of these materials lead to relatively very large carrier storage in the junction transition region, as compared with that present in Ge devices. Thus the error introduced by this storage for Si solar cells, particularly highly efficient solar cells in which the carrier storage and recombination in the quasineutral base is small, invalidates the conventional transient methods.

A.   IMPROVEMENTS IN THE CIRCUIT FOR THE SHORT-CIRCUIT CURRENT
       DECAY

We have improved the circuit relative to that reported in Jung, Neugroschel, and Lindholm (1984). An MOSFET switch (Fig. 1) replaces our former more complicated and slower switching circuit (Fig. 3 of Jung, Neugroschel, and Lindholm, 1984). Part (b) of Fig. 1 shows the observables for t>0. These consist of a slope and an intercept. The relevant theory appears in Jung, Neugroschel, and Lindholm (1984).

The circuit of Fig. 1 offers significant advantages. Our previous circuit led to a relatively slow establishment of the short-circuit conditions. For certain solar cells, this made

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impossible the determination of S and τ. The circuit of Fig. 1 switches in approximately 10 ns., and no problems exist in interpreting the lifetime and S of any of the over ten solar cells of different types we have treated.

B. REMARKS ON SENSITIVITY

Figs. 2(a) and (b), developed from theory, illustrate aspects of the sensitivity of the SCCD method. Let L = minority-carrier diffusion length. Let W = quasineutral base thickness. Then for thin cells (W<<L) the method is sensitive to S because most minority carriers recombine at the back surface. Conversely, for thick cells, W>>L, the method is sensitive to τ but not to S.

In the limiting cases just described, the SCCD method will yield only one of the desired parameters, either τ or S. To determine the other parameter requires another added measurement that depends both on S and τ (or L). For example, on can use the dark reverse saturation current or the open-circuit voltage. Both of these parameters may be influenced by quasineutral emitter recombination. Thus error can occur.

C. SMALL-SIGNAL ADMITTANCE

This technique works well as the needed supplement. Neugroschel (1984) has described details of the application of this technique as a supplement to SCCD. This work resulted as part of an ongoing collaboration between the present Principle Investigator and Prof. Neugroschel. Graduate Research Student, T. W. Jung, is continuing these efforts.

D.   REPRESENTATIVE RESULTS

These appear in Table 1. Although over ten different solar cells were measured using SCCD, we ruport six here, relegating further reporting to the future when the detailed physical make-up of the solar cells involved become available.

III. POLYSILICON/SILICON HETEROJUNCTIONS APPLIED TO SOLAR
CELLS

Replacement in Si bipolar junction transistor of the
metal emitter contact by a highly doped polysilicon layer
improves the common-emitter current gain of bipolar
transistors. The principal investigator has reviewed some
twenty papers dealing with this issue, prominent among which
are (de Graaff and de Groot, 1979), (Ning and Isaac, 1980) and
(Eltoukhy and Roulston, 1982). According to de Graaff and de
Groot (1979) and to Green and Godfrey (1983), this replacement
can lead to common emitter current gain $\beta > 1000$, which
contrasts with $\beta \approx 100$ in the traditional metal-contact
bipolar transistor.

This ten-fold increase in β corresponds directly to a
ten-fold decrease of the recombination current in the n+
emitter. Thus arises the implications for solar cells. The
ten-fold decrease can only come from the presence of an
effective surface recombination velocity S at the
n+Si/n+polySi interface. Recent work by NEUGROSCHEL (1984),
helped to some degree by the principal investigator, resulted
in the conclusion that $S << \sim 10^4$ cm/s.

The physical mechanisms responsible for the decrease in

S are complicated by a lack of knowledge of the minority-
carrier diffusivity in both the n+ monoSi and polySi, and by a
poor present understanding of the interfacial layer. The
parameters of this layer are highly sensitive to fabrication
conditions and to surface treatment before the CVD process of
polysilicon deposition. Various investigators have explored
the chemistry of the interface, where peaks in P or As can
occur, where deep-level impurities and interstitial oxygen may
occur, and a thin insulating interfacial layer can be created
by thermal oxidiation or chemical treatments before CVD
deposition.

But one thing is clear. The polysilicon/silicon
heterojunction acts as an effective surface passivant,
reducing recombination losses. Various investigations suggest
strongly that the ability to passivate persists in the
presence of sunlight.

Several possibilities exist for exploiting this
passivant for Si solar cells. Details about these
possibilities appear in the recent proposal to JPL by the
author.

IV.   RECOMMENDATIONS AND CONCLUSIONS

The short-circuit current decay method is apparently the only reliable transient electrical method for determining τ and S for a wide variety of Si solar cells. For very thin or very thick devices, this method must be supplemented. Otherwise only τ or only S can be determined accurately, not both. The small-signal admittance method appears to fill this need. Our continuing work will explore this issue more fully.

As recommendations, we offer the following:

(a) Other laboratories, including JPL, would benefit by setting up the SCCD method. Full details about set-up will appear in the final report.

(b) The open-circuit voltage decay needs development for use in connection with manufacturing lines (see quarterly 2). This requires implementation of expressions for junction capacitance under forward voltage. These have been developed under this contract support, but are not yet written.

(c) Measurement of the lifetime and the front surface recombination velocity of the quasineutral emitter is essential. Because dc steady-state methods will yield τ only as part of a product ($D\tau$, for example), one must also independently measure D and μ of the minority carriers.

V. REFERENCES

Jung, T. W., F. A. Lindholm, and A. Neugroschel, 1984, IEEE Trans. Electron Devices, 31, 588.

Table I: Summary of results for some typical solar cells. The values for L_{base} and S_{eff} were obtained using the SSCD method, unless marked otherwise

CELL	ρ_{base} (Ωcm)	W_{base} (μm)	L_{base} (μm)	S_{eff} (cm/sec)
n$^+$/p/p$^+$ BSF	10	227	454 / 450*	105
n$^+$/p/p$^+$ BSF	10	103	250	2.9×10^3
n$^+$/p/p$^+$	10	360	512	2×10^5
n$^+$/p/p$^+$	0.15	295	100	---
p$^+$/n/n$^+$ BSF	10	320	80$^+$	503* / 500†
n$^+$/p/p$^+$ BSF	10	92	~600*	~180

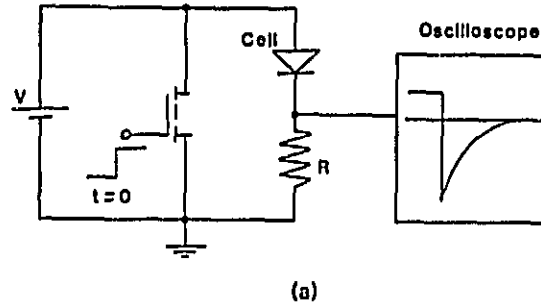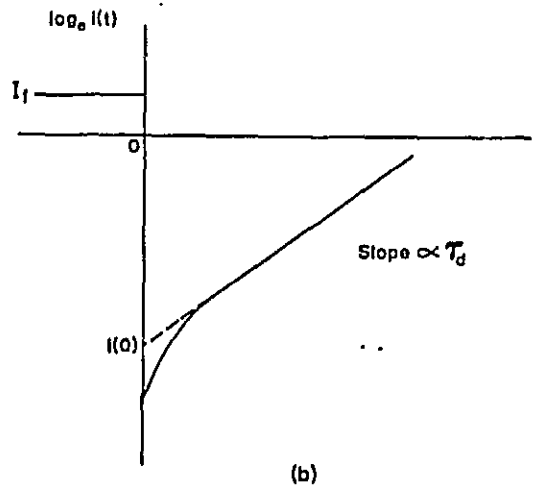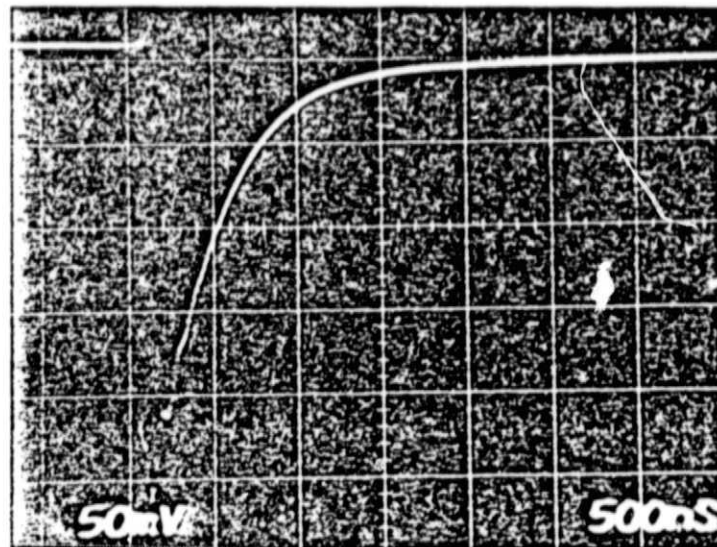* obtained from G_{QN}^{HF}

† obtained from G_{QN}^{LF}

Fig. 1. (a) Electronic circuit used in the SCCD method. The switching time of a power MOST is less than 100 nsec.

(b) Schematic illustration of the current decay displayed on a log scale.

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(c) Experimental current decay for a $n^+/p/p^+$ BSF solar cell ($\rho_{base} \approx 0.3$ Ωcm, $W_{base} \approx 367$ μm, $\tau_d \approx 6.4$ μsec, $L_n \approx 180$ μm, $S_{eff} \approx 1.3 \times 10^3$ cm/sec). The vertical scale is 100 mA/division.

(a)

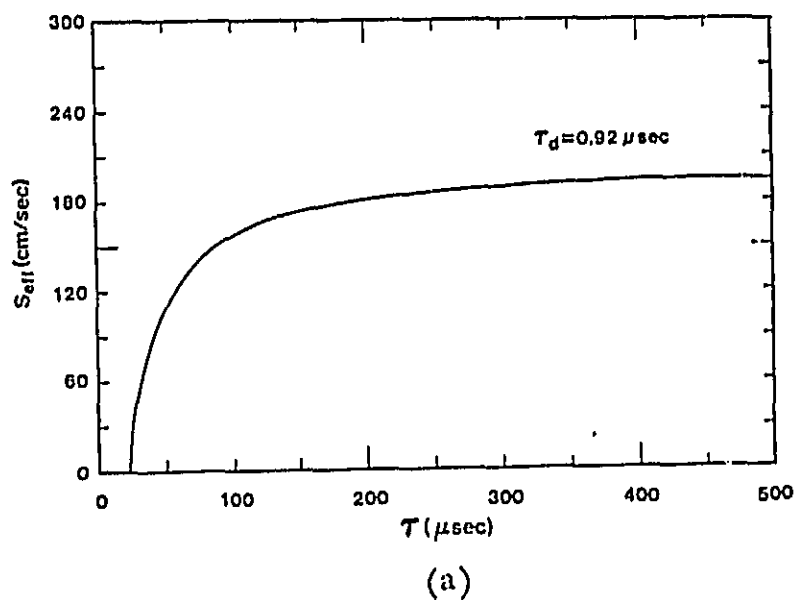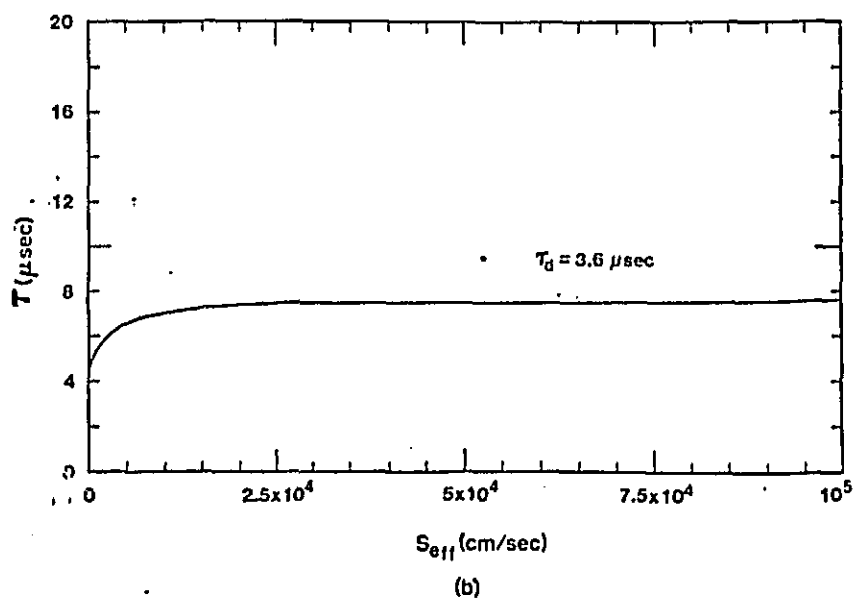Fig. 2. (a) Plot of S_{eff} vs τ for a thin $n^+/p/p^+$ BSF solar cell ($\rho_{base} \simeq 10$ Ωcm, $W_{base} \simeq 92$ μm).

(b)

(b) Plot of τ vs S_{eff} for a thick $n^+/p/p^+$ BSF solar cell ($\rho_{base} = 0.15$ Ωcm, $W_{base} \simeq 295$ μm).